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THE EARTH AS AN ANTINEUTRINO STAR

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Abstract. Antineutrinos are emitted in the Earth upon β decays of radioactive elements and reach the surface with little interaction with terrestrial materials. These antineutrinos are anticipated to carry unique information about the chemistry and energetics of the Earth. We make a systematic search for the candidate target materials that undergo nuclear reactions with incoming antineutrinos and therefore that could be used as an antineutrino detector. The target nuclides most preferable for the measurement are ^{3}He and ^{1}H. For ^{3}He we suggest a liquid ^{3}He scintillation counter, of which practicability depends on the feasibility of amassing at least 10 ton of ^{3}He. For ^{1}H we may design a H_2O or liquid H_2 scintillation counter with an appropriate activator, which should be capable of detecting scintillation light in a huge tank containing at least 10^4 ton of H_2O or 10^3 ton of H_2.

Introduction

Neutrino and its antiparticle, antineutrino, have no electric charge and zero or a very little mass. They interact with other materials only through weak-interaction so that, in spite of their fullness in universe, there are few opportunities to detect them. There are several sources of neutrino and antineutrino in the cosmic space and we are in the " sea of neutrinos" (Krauss *et al.*,1984). Solar neutrinos have been observed for more than fifteen years in U.S.A. (Bahcall and Davis,1976), exhibiting a serious discrepancy between the observed and theoretical solar neutrino fluxes (Bahcall *et al.*, 1988). Neutrinos and antineutrinos of supernova origin were for the first time detected in 1987 (Hirata*et al.*,1987 and Biontait et al.,1987). This has opened the window to neutrino astronomy.

Antineutrinos are also generated within the Earth upon beta decays of radioactive isotopes and thus should provide us with the most direct evidence for the abundance of radioactive elements. The importance and possibility of detecting terrestrial antineutrinos have been pointed out and discussed by Eder(1966), Marx(1969), Avilez *et al.* (1981) and Krauss *et al.* (1984). We add, in this paper, an intriguing possibility of the extra flux of antineutrino from the core.

According to Krauss *et al.* (1984) the experimental difficulty with regard to terrestrial antineutrino detection is similar to that at the time when the first experiments for solar neutrinos were designed. In view of the importance of the problem of measuring terrestrial antineutrino flux, we will make a systematic search for the possible antineutrino reaction that could be used for detecting terrestrial antineutrinos. The main aim of this search is to suggest a feasible experiment that may be realized in the future. Our approach is essentially the same as Krauss *et al.*(1984) who limited their consideration to the case where the target is some kind of nucleus.

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Terrestrial Antineutrino Flux

Antineutrinos from the Earth's interior are emitted at beta decays of elements :

$$[A,Z] \rightarrow [A,Z+1] + e^- + \bar{\nu}, \qquad (1)$$

where $[A,Z]$ means a nucleus with mass number A and atomic number Z, e^- is an electron and $\bar{\nu}$ is an antineutrino. We define F_0, flux of terrestrial antineutrino, as the number of antineutrinos outgoing through unit area of the Earth's surface per unit time. This flux may be expressed as

$$F_0 = \lambda \cdot \frac{SMI}{m} \cdot N_a \cdot \frac{1}{4\pi R^2} \qquad (2)$$

where λ is the decay constant of beta decay (1), S the abundance of the relevant element with atomic weight m relative to the mass M of the Earth, I the isotope ratio of the radiogenic nuclide, N_a the Avogadoro's number and R the radius of the Earth. To calculate S, we use the model of Ganapathy and Anders (1974) for the bulk chemical composition of the Earth. Table 1 lists the estimated values of flux F_0. The total flux of terrestrial antineutrino amounts to $8.9 \times 10^6/cm^2/sec$ on the surface of the Earth, to which ^{40}K,^{232}Th and ^{238}U contribute mainly. Several hundred millions of antineutrinos are to go through our body in every second.

The antineutrino flux in an energy range from E to E+dE is given by:

$$F(E)dE = F_0 \frac{1}{(m_e c^2)^5} \frac{1}{f} E^2 (E_0 - E)\sqrt{(E_0 - E)^2 - (m_e c^2)^2}\, dE \qquad (3)$$

where m_e is the mass of electron, f the f-value of beta decay (1), and E_0 the decay energy in beta decay (Sugimoto and Muraoka, 1973). Figure 1 shows the energy spectrum $F(E)$. The inherent spectral shape for a particular source nuclide suggests a possibility of identifying the source nuclides by measuring the energy of terrestrial antineutrinos. Such identification would help better understanding the chemical composition of the deep interior of the Earth and how much energy is released by radioactive decays. In the model of Ganapathy and Anders (1974), the abundance of K in the Earth is 1/5 of the

Table 1. Estimated terrestrial antineutrino fluxes

Source nuclide	E_{MAX} [MeV]	Half life [year]	Abundance [ppm]	Flux [$cm^{-2}\,sec^{-1}$]
^{40}K	1.311	1.28×10^9	170	5.3×10^6
^{87}Rb	0.272	4.8×10^{10}	0.58	6.1×10^5
^{176}Lu	1.187	2.0×10^{10}	0.049	5.7×10^3
^{187}Re	0.0026	4.3×10^{10}	0.076	9.2×10^4
Th decay chain				
^{232}Th		1.4×10^{10}	0.065	1.1×10^6
^{228}Ra	0.046			3.1×10^5
^{228}Ac	2.138			3.1×10^5
^{212}Pb	0.573			3.1×10^5
^{212}Bi	2.246			2.0×10^5
Ac decay chain				
^{235}U		7.0×10^8	0.018	7.6×10^4
^{231}Th	0.389			1.2×10^4
^{227}Ac	0.034			1.2×10^4
^{223}Fr	1.148			1.2×10^4
^{219}At	1.700			3.6×10^3
^{215}Bi	2.249			1.2×10^4
^{211}Pb	1.373			1.2×10^4
^{207}Tl	1.422			1.2×10^4
U-Ra decay chain				
^{238}U		4.5×10^9	0.018	1.6×10^6
^{234}Th	0.263			2.6×10^5
^{234}Pa	2.207			2.6×10^5
^{214}Pb	1.024			2.6×10^5
^{214}Bi	3.270			2.6×10^5
^{210}Pb	0.063			2.6×10^5
^{210}Bi	1.161			2.6×10^5
Total				8.9×10^6

cosmic abundance. Such a depletion is common to most of the Earth models. Lewis (1971), however, postulated a hypothesis that this 'missing K' was partitioned into the metallic melt and descent with it into the central part of the Earth at the time of core formation. The Earth's core consists of mainly Fe-Ni alloy and of 10 or 20 % of other lighter elements (Stacy, 1972). If the lighter elements are dominated by sulfur (Murthy and Hall, 1970), potassium would be indeed contained in the core because of its affinity with iron sulfide. Radiogenic heat of this "missing" ^{40}K has been estimated to be large enough to sustain geomagnetic dynamo in the core, where it may be otherwise difficult to find its power source (Verhoogen, 1973; Goettel, 1976). The broken curve in Fig.1 shows the spectrum with the abundance of K 5 times as large as the model abundance, corresponding to the case of no loss of potassium from the Earth through its history. The difference between the solid and broken curves suggests that accurate determination of antineutrino spectrum might resolve the presence or absence of K in the core.

Detection of Terrestrial Antineutrinos

Any method of detection uses in principle a reaction of antineutrinos with some target to count the number of its products that may reflects the real flux of terrestrial antineutrino. Krauss *et al.* (1984) considered nuclear reactions in which the target is some kind of nucleus. We make a more systematic search for the feasibility of this type of reaction to be used to detect terrestrial antineutrinos. Let N_T be the number of the target nuclei in a target on the Earth's surface, and N_P the number of the product nuclei:

$$dN_P = RN_T dt, \tag{4}$$

where R is the reaction rate defined as the number of the reaction occurring in unit time per one target nucleus, and it is measured in TAU (Terrestrial Antineutrino Unit $= 10^{-36}$ reactions per second per one target nucleus).

When a certain nuclide P undergoes beta decay to change itself into the daughter nuclide T:

$$P \rightarrow T + e^- + \bar{\nu} + Q, \tag{5}$$

the following two reactions can occur:

$$\bar{\nu} + T \rightarrow P + e^+ : \quad Inverse\ \beta^-\ decay, \tag{6a}$$

$$\bar{\nu} + e^- + T \rightarrow P : \quad Resonant\ electron\ capture, \tag{6b}$$

where Q is the total kinetic energy of the emitted electron and antineutrino. The cross section of inverse beta decay (6a) is given by:

$$\sigma(E \geq E_{th}) = s \cdot 2\pi^2 ln2 \left(\frac{1}{mc}\right)^5 \left(\frac{\hbar}{c}\right)^3 F_e(Z,E) \frac{1}{ft} E\sqrt{E^2 - (m_e c^2)^2}, \tag{7}$$

(Sugimoto and Muraoka, 1988) where E is the kinetic energy of incident $\bar{\nu}$ and E_{th} is the energy threshold of reaction defined by

$$E_{th} = Q + 2m_e c^2 = E_0 + m_e c^2,$$

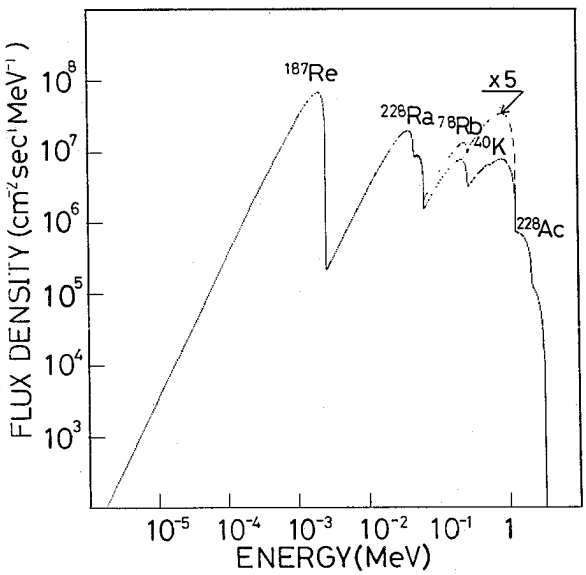

Figure 1. Estimated terrestrial antineutrino spectrum (solid line) for the Earth model of Ganapathy and Anders (1974). Different peaks correspond to different beta decay nuclides. Also shown are the hypothetical extra fluxes from the core due to excess ^{40}K in the core (broken line: the total K 5 times as abundant as the model abundance).

E_0 being the decay energy of beta decay (5). The spin statistical factor s is $s = (2I_P + 1)(2I_e + 1)$ where I_P and I_e are the spins of nucleus P and emitted positron e^+, Fe(Z,E) the Fermi function for atomic number Z, and ft the ft value of reaction (5). Reaction rate R is given by

$$R = \int_{E_{th}}^{E_{max}} \sigma(E)F(E)dE,$$

where F(E) is the antineutrino flux shown by the solid line in Fig.1 and E_{max} is $E_0 - m_e c^2$ in (3). The cross section of resonant electron capture (6b) is given by:

$$\sigma(E = E_{res}) = 8\pi^2 ln2\,\hbar \left(\frac{\hbar}{m_e c}\right)^5 \frac{s}{ft} |\psi(R_0)|^2 \varrho(E_{res}), \quad (8)$$

(Mikaelyam *et al.*, 1968) where s is the spin statistical factor ($s = 2I_P + 1$; I_P: spin of nucleus P), $\psi(R_0)$ the wave function of a K-shell electron at the surface of T nucleus, E_{res} the resonant energy equal to Q, and $\varrho(E)$ the antineutrino energy spectral density. Reaction rate R is given in this case as

$$R = \sigma(E_{res})F(E_{res}).$$

We consider the target as a closed system except for incident antineutrinos. Nuclide P produced through the process of either (6a) or (6b) decays again to nuclide T through the process of (5). Taking this reaction into account, eq.(4) is rewritten as

$$\frac{dN_P}{dt} = R N_T - \lambda N_P, \quad (9)$$

where λ is the decay constant of the beta decay of P. This equation suggests two types of detecting experiment. The first is to measure directly the total reaction rate in a detector carefully designed at the Earth's surface (real-time detection). In this case, we count ΔN_R, the number of the reactions occurring in the target in a time interval Δt ($\lambda \Delta t \ll 1$) and calculate reaction rate R from

$$R = \frac{\Delta N_R}{N_T \Delta t} \quad (10)$$

where N_T represents the number of T in the target. The second type of experiment is to detect product element P of the antineutrino reaction by means of isotope analysis in target nuclide T-bearing rocks of ages longer than λ^{-1} (geochemical detection). In this case, we would obtain N_P/N_T in a saturated state of the rock system where $dN_P/dt \sim 0$ and calculate reaction rate R from

$$R = \lambda \frac{N_P}{N_T}. \quad (11)$$

Calculated reaction rates and saturated P/T ratios for various candidate nuclides are listed in Table 2. Candidates were selected from the three points of view. (I) Elements with low ft values: a low ft values results in a high reaction rate as may be understood from Eqs. (7) or (8). (II) Elements abundant in the crust: such an element is advantageous for preparing the target material of huge amount. (III) Elements whose products are noble gases: in this case it is easy to count the number of the product element in a large amount of target material.

Table 2. Candidates of target for terrestrial antineutrino detection

Target	E_{th} [MeV]	Reaction Rate [TAU*]	Saturated P/T ratio	N_T^{**} [kg]
Elements with low ft values				
^{187}Os	1.025	6.3×10^{-8}	1.3×10^{-25}	5.6×10^{13}
^{3}He	1.041	2.1	1.2×10^{-27}	27000
^{107}Ag	1.055	3.3×10^{-7}	9.7×10^{-29}	6.3×10^{12}
^{131}Eu	1.098	1.2×10^{-3}	4.6×10^{-30}	2.5×10^{9}
^{93}Nb	1.114	7.3×10^{-8}	5.0×10^{-30}	2.5×10^{13}
^{171}Yb	1.119	9.1×10^{-3}	8.2×10^{-31}	3.6×10^{8}
^{14}N	1.179	7.5×10^{-7}	2.0×10^{-31}	3.6×10^{11}
^{79}Br	1.181	1.9×10^{-7}	5.7×10^{-31}	7.8×10^{12}
^{35}Cl	1.190	3.7×10^{-5}	4.0×10^{-34}	1.8×10^{10}
^{135}Ba	1.227	1.6×10^{-9}	2.1×10^{-31}	1.7×10^{15}
^{155}Gd	1.268	1.5×10^{-4}	3.3×10^{-32}	2.0×10^{10}
^{33}S	1.271	1.2×10^{-2}	3.8×10^{-32}	5.3×10^{7}
^{169}Tm	1.374	3.2×10^{-3}	3.7×10^{-33}	1.0×10^{9}
^{121}Sb	1.409	6.7×10^{-2}	9.4×10^{-33}	3.5×10^{7}
^{185}Re	1.454	7.1×10^{-3}	6.6×10^{-32}	5.0×10^{8}
^{199}Hg	1.475	9.1×10^{-4}	3.6×10^{-34}	4.2×10^{9}
^{175}Lu	1.490	1.8×10^{-2}	9.2×10^{-33}	1.9×10^{8}
^{177}Hf	1.519	9.2×10^{-3}	7.7×10^{-33}	3.7×10^{8}
^{64}Zn	1.600	7.6×10^{-3}	1.3×10^{-33}	1.6×10^{8}
^{141}Pr	1.602	3.3×10^{-4}	1.3×10^{-33}	8.2×10^{9}
^{113}In	1.608	9.2×10^{-6}	5.9×10^{-33}	2.4×10^{11}
^{161}Dy	1.613	1.9×10^{-4}	1.7×10^{-34}	1.6×10^{10}
^{77}Se	1.712	4.0×10^{-3}	8.1×10^{-34}	3.7×10^{8}
^{153}Eu	1.827	5.8×10^{-4}	1.4×10^{-34}	5.1×10^{9}
Elements abundant in the crust				
^{1}H	1.804	4.2×10^{-3}	3.8×10^{-36}	4.6×10^{6}
^{27}Al	3.631	4.4×10^{-7}	3.6×10^{-40}	1.2×10^{12}
^{43}Ca	2.839	6.3×10^{-6}	7.3×10^{-37}	1.3×10^{11}
^{31}P	2.513	4.0×10^{-4}	5.5×10^{-36}	1.5×10^{9}
^{39}K	1.587	4.5×10^{-7}	5.5×10^{-33}	1.7×10^{12}
^{47}Ti	1.623	1.1×10^{-2}	4.7×10^{-33}	8.2×10^{7}
^{63}Cu	1.087	8.1×10^{-4}	3.7×10^{-30}	1.5×10^{9}
^{95}Mo	1.948	1.0×10^{-4}	4.5×10^{-34}	1.8×10^{10}
^{204}Pb	1.785	5.9×10^{-6}	1.1×10^{-33}	6.6×10^{11}
^{206}Pb	2.548	5.8×10^{-3}	2.1×10^{-36}	6.8×10^{8}
^{207}Pb	2.444	1.1×10^{-2}	4.4×10^{-36}	3.8×10^{8}
Elements of which products are noble gases				
^{85}Rb	1.709	4.7×10^{-6}	2.3×10^{-33}	3.5×10^{11}
^{133}Cs	1.499	6.2×10^{-3}	4.1×10^{-33}	4.1×10^{8}

* 1 TAU=10^{-36}reactions/target atom· sec

** Necessary amount for one reaction per one day

Table 2 also shows how much target material is necessary to observe one reaction per one day. For real-time measurement, the most preferred target nuclide is ^{3}He. It needs 27 ton of ^{3}He to detect one antineutrino event per one day. ^{1}H should also be noted. The detection requires 4600 ton of ^{1}H, which is not inaccessible. Except for ^{3}He and ^{1}H, target material appears to be of inaccessively large amount. The saturated P/T ratio listed in Table 2 can be understood as a necessary sensitivity for isotope analysis in geochemical detection. The value is at best of the order of 10^{-25}. It is difficult to obtain such a high sensitivity at the present stage, and therefore it is practically impossible to detect terrestrial antineutrinos by means of geochemical method.

Discussion

To use ^{3}He as the target material, we may design a liquid ^{3}He scintillation counter. The reaction to be detected is

$$^3\mathrm{He} + \bar{\nu} \rightarrow {}^3\mathrm{H} + e^+. \qquad (12)$$

Since ^{3}He itself can be used as a scintillatior, we may observe scintillation light from the emitted positron and from the gamma ray at pair annihilation of positron and electron. An array of high sensitivity photomultiplier should be placed in a ultra low temperature ^{3}He tank. If we can reduce background events to a sufficiently low level, we may obtain the energy spectrum of terrestrial antineutrino by measuring the kinetic energy of the emitted positron. The threshold energy of reaction (12) is 1.04 MeV, implying that this detector has a sensitivity for antineutrinos from ^{238}U series, ^{232}Th series and ^{40}K. Thus, this detector covers the major radioactive elements in the Earth. At least 10 ton of ^{3}He would be necessary for a realistic experiment, where one event may be detected in about 3 days. At present, preparation of such amount of ^{3}He is probably the main difficulty for the detection. A possibility would arise if a nuclear fusion reactor in the future utilizes the D-D reaction which produces ^{3}He as a reaction product.

In contrast, a ^{1}H detector has no difficulty to prepare the target material. We may design a H_2O or liquid H_2 scintillation counter with an appropriate acitivator in it. The reaction to be detected is

$$^1\mathrm{H} + \bar{\nu} \rightarrow \mathrm{n} + e^+, \qquad (13)$$

where n is neutron. Note that this reaction has not been examined in the previous studies. The threshold energy of this reaction is 1.804 MeV, so the detector has a sensitivity for ^{238}U and ^{232}Th. Detection of one event in one day needs 41,000 ton of H_2O or 4,600 ton of H_2. In this case, new technology may be required to detect scintillation light in a huge tank of H_2O or liquid H_2.

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